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SALT and RR Lyrae Variables: Our Galaxy, The Magellanic Clouds and the Local Group

Michael Feast

*Astronomy Department, University of Cape Town, Rondebosch, 7701,
South Africa.
mwf@artemisia.ast.uct.ac.za*

Abstract. A review is given of the possibilities for the study of the kinematics and metallicities of the old populations in galaxies of the Local Group using SALT/PFIS observations of RR Lyrae variables.

1. Introduction

In her summary talk at the recent Carnegie Cosmology conference, Sandra Faber (2003) made two predictions:

1. “The major era of chasing cosmological parameters is now closing”
2. “Understanding galaxy formation.....will continue to occupy cosmologists for some time.....But there is no fundamentally new physics ¹ to be discovered there.”

These are bold, perhaps rash, predictions, of the kind that are often falsified by observations and SALT could well play a part in such falsification.

As regards galaxy formation, structure, and evolution, one gets some flavour of the present situation by considering the dwarf spheroidal galaxies which are often considered the simplest of systems. Below are summarized the conclusions of some papers, all on dwarf spheroidals, published in the last few months.

On the one hand:

Dwarf spheroidals are formed by the coalescing of clusters in dark matter halos.
(astro-ph/0309202)

On the other:

Draco and UMi are weakly unbound systems - no significant dark matter.
(astro-ph/0309207)

But:

Draco is not the remnant of a tidally disrupted satellite but probably is strongly dark matter dominated.

(ApJ 589, 798, 2003)

Though:

It is impossible to reproduce the tidal tail of UMi if it has a large dark matter

¹As distinct, presumably, from new and unusual applications of known physics.

content.

(ApJ 586, L123, 2003)

But again:

UMi is one of the most dark matter dominated galaxies known.

(ApJ 588, L21, 2003)

And finally:

The extended outer structure of UMi could be extra-tidal stars either unbound or within a dark matter halo.

(AJ 125, 1352, 2003)

I think it might be fair to summarize the above by saying that, not only do we not know what dark matter is, we are not certain where it is, and some would even say, if it is. It is worth noticing in passing that it has recently been suggested (Scarpa et al. 2003) that some globular clusters may contain dark matter or that modified Newtonian dynamics is required.

As for Our Own Galaxy, it has been commonly supposed that its halo was formed by the infall of dwarf-spheroidal-like objects. It was also a rather general belief that the halo of Our Galaxy is typical of the halos of spirals. However, we now know that the abundance of the α elements (i.e. $[\alpha/\text{Fe}]$) in dwarf spheroids is not similar to their abundance in our halo (e.g. Shetrone et al. 2003, Tolstoy et al. 2003). Evidently infalling dwarf spheroidals are not the major source of at least the inner halo of Our Galaxy. Furthermore, recent work (Brown et al. 2003) suggests that the halo of M31 is distinctly different from that of Our Galaxy. Thus bringing into question the notion of a “typical” halo.

It is clear that the current need is for detailed studies of the internal structure and kinematics of all types of galaxies as a function of the chemical compositions and ages of their component populations.

2. Variable stars and SALT

In carrying out programmes of this type we need in each galaxy to isolate homogeneous groups of objects. Variable stars are particularly useful in this respect and amongst the variables there are three particularly useful types. These are the Cepheids which trace young, metal rich populations (the disc in Our Galaxy); RR Lyraes, old metal-poor objects, which trace halo-type populations; and, the Miras which, as a function of period, trace much of the intermediate age populations. These three types of variable star can be used to study the distances, kinematics and distributions of different populations in Our Galaxy, in the Local Group and, in some cases in more distant galaxies.

SALT is coming into operation in the era of massive variable star surveys. This offers great opportunities and will doubtless have a major effect on SALT programmes. MACHO, OGLE, MOA, SLOAN, QUEST are just some of the more obvious current surveys. Such surveys will undoubtedly be extended in the future either with the direct aim of finding variables or else finding them as a by-product. For instance, planned surveys of the sky for near-earth objects should also find variables in large numbers. Not only are surveys finding very large numbers of variables to faint limits, but they are being found in systematic

ways which is of great importance in their use. In addition to this, surveys such as 2MASS allow potential variables to be selected by their colours.

3. The RR Lyrae Variables

Of the three main types of variable star mentioned above, this paper will concentrate on the RR Lyrae variables. It is in some ways quite appropriate to discuss here the potential of SALT for studying these stars in our own and other galaxies. Just over 50 years ago when the 1.9m telescope, now at Sutherland and then in Pretoria, was the largest telescope in the southern hemisphere, David Thackeray and Adriaan Wesselink used it to discover the first RR Lyrae variables in the Magellanic Clouds and Thackeray used it to prove that the Hubble-Baade variables in the Sculptor dwarf spheroidal were indeed RR Lyraes. These two discoveries were of major importance. The first, increased the distance modulus of the Clouds by 1.5mag and was the most decisive evidence for a major increase in the extragalactic distance scale. The second, was particularly important in the context of the population scheme that Baade was then proposing. The historical background to this work is given in the Baade-Thackeray correspondence (Feast 2000).

RR Lyrae variables are found in globular clusters as well as the general field. They are indicators of old, metal-poor populations, with $[Fe/H]$ ranging from about -0.5 to -2.5 . Their pulsation periods range from about 0.4 to 1.0 days if they are fundamental pulsators (the “ab” type) or about 0.2 to 0.5 days if they are overtone pulsators (“c” type). Table 1 lists some estimates of their absolute magnitudes.

Table 1. The Absolute Magnitude of RR Lyrae variables at $[Fe/H] = -1.5$

Method	M_V	reference
Parallax (HST)	$+0.62 \pm 0.16$	Benedict, et al. 2002 ¹
Parallax (Hipparcos)	$+0.40 \pm 0.22$	Koen & Laney 1998
Horizontal Branch	$+0.63 \pm 0.12$	Gratton 1998
Globular Clusters	$+0.47 \pm 0.12$	Carretta et al. 2000
δ Scuti variables	$+0.49 \pm 0.10$	McNamara 1997
Statistical parallaxes	$+0.79 \pm 0.13$	Gould & Popowski 1998
Adopted Mean	+0.58	

¹ see Feast (2002)

The adopted mean gives half weight to the result from Hipparcos parallaxes because this has a large standard error. Some of the other values may not be as well determined as their standard errors might imply. For instance the statistical parallax solution depends on a simple model of the galactic halo. Using the photometry of RR Lyraes in the LMC (e.g. Clementini et al. 2003) with the adopted value of M_V leads to an LMC distance modulus of 18.53 in good agreement with other values (see e.g. Feast 2003).

It has been known for some long while that the absolute magnitude of RR Lyrae variables depends on their metallicity. In its simplest form this relation-

ship can be written as:

$$M_V = \alpha[Fe/H] + \gamma \quad (1)$$

The M_V values given in Table 1 are for $[Fe/H] = -1.5$ assuming $\alpha = 0.18$, a value often used. There has been considerable discussion of the true value of α . One reason that this is important is that it affects the relative distances of globular clusters of different metallicities when using RR Lyraes as the distance indicator. These distances determine the absolute magnitudes at the main sequence turn-off and thus the cluster ages. If $\alpha = 0.18$, metal-poor clusters ($[Fe/H] \sim -2.2$) are older than metal-rich ($[Fe/H] \sim -0.7$) clusters by about 3Gyr. If however, $\alpha = 0.39$ (Sandage 1993), then all globular cluster would be about the same age, independent of metallicity (see e.g., Sandage & Cacciari 1990). Thus, establishing the dependence of RR Lyrae absolute magnitudes on metallicity is of important for understanding the early history and evolution of Our Galaxy.

RR Lyrae variables are ideal spectroscopic targets for SALT. Photometry, from large scale surveys is, or will be, available; the short periods of the variables limit the possible exposure time to less than 30min (or perhaps 60min for the longer period stars), and their radial velocities and metallicities can be adequately determined, for many purposes, at modest resolution (say $R \sim 1000$) well within the range of PFIS. Thus they will be good targets for the first generation of SALT instrumentation. RR Lyrae metallicities are generally estimated using the method devised by Preston (1959). This method compares the strengths of the Balmer lines with that of the CaII(K) line, leading to a quantity ΔS which can be calibrated as a function of $[Fe/H]$ from high resolution observations of nearby RR Lyraes. (For discussions of the calibration and accuracy of the method see for instance: Suntzeff et al. 1991, Clementini et al. 1995, Lambert et al. 1996, Solano et al. 1997, Fernley and Barnes 1997.)

4. RR Lyraes and the LMC

Until recently the only spectroscopic metallicities known for LMC RR Lyraes were of six stars observed with the ESO 3.6m telescope at $R \sim 450$ and using the ΔS method (Bragaglia et al. 2001). However, a short paper and a conference proceedings have now appeared giving some results from the VLT. It is useful to look at these preliminary data in some detail as it gives some idea of what may be achieved with SALT both in the Magellanic Clouds and elsewhere.

Both these studies used the VLT with the FORS1 instrumentation. This has a field of view of 7×7 arcmin, somewhat smaller than SALT/PFIS, and 19 slitlets. Note that FORS2 has the same size field but, like PFIS, can accommodate more slits. Minniti et al. (2003) obtained two exposures of 20 min on each of six fields in the LMC bar. There were five to ten RR Lyraes per field and the resolution was about 1000. Photometry (e.g. Clementini et al. 2003, Soszyński et al. 2003b) indicates that these stars are at $V \sim 19.3$ and $B \sim 19.7$. From these spectra Minniti et al. made an estimate of the velocity dispersion. To do this they needed to correct the observed velocities for pulsational effects (since they did not have full velocity curves). This correction was made using a standard template with the phase of the programme star known from pub-

lished photometry ² The velocity dispersion derived then needed to be corrected for the scatter introduced by the template method and also for the estimated uncertainty in the radial velocity measurements. Table 2 shows their results.

Table 2. Velocity Dispersion of LMC RR Lyraes (Minniti et al. 2003)

Measured	61 ± 7
Phase correction	20
Measuring uncertainty	22
“True” dispersion	53 ± 10
	km s^{-1}

This result is of interest because the estimated dispersion is larger than that of other objects in the LMC: i.e. young population, $\sim 9 \text{ km s}^{-1}$; Planetary nebulae, $\sim 20 \text{ km s}^{-1}$; Miras, $\sim 33 \text{ km s}^{-1}$. However, it is clearly only a fore-taste of what might be done.

The other VLT/FORS1 study (Clementini 2003) summarizes the [Fe/H] results from Preston’s ΔS (resolution about 800) for about 100 RR Lyraes in the LMC Bar. From a plot of V_o against [Fe/H] Clementini and her co-workers find that α in equation 1 above is 0.21. However, their figure 2 shows that this value is still rather uncertain, due mainly to the few points at high and low metallicities. Considerably higher or lower values cannot at present be ruled out. Most of the points lie in the range, [Fe/H] -1.2 to -1.8 . An estimate of the distribution of these points together with the quoted uncertainty of a single value ($\sigma_{[\text{Fe}/\text{H}]} = 0.2$) suggests that much of the scatter in [Fe/H] is observational. Evidence from galactic work (see e.g., Suntzeff et al. 1991) suggests that it should be possible to derive relative [Fe/H] values by the ΔS method with an uncertainty of about 0.1 and this will be necessary to study the distribution of RR Lyrae metallicities in the LMC in detail.

The two investigations just described suggest that with sufficient stars and careful (and probably repeated) observations, it will be possible to study the kinematics and metallicities of RR Lyraes (and their relationship) as a function of position in the LMC. With care it may even be possible to study the kinematics and metallicities as a function of depth in the LMC. $\Delta V_o = 0.5 \text{ mag}$ corresponds to a depth in the line of sight of $\sim 12 \text{ kpc}$ at the distance of the LMC and for a spherical subsystem this would be equivalent to a diameter of $\sim 14^\circ$ on the sky; a not unreasonable size for such a subsystem.

The current position regarding the discovery of RR Lyraes in the general field of the LMC is as follows. The OGLE II survey (Soszyński et al. 2003b) which covered 4.5 sq.deg. over the Bar region, has given data for 7600 RR Lyraes variables. This is an average of about 26 variables per PFIS field. Numbers drop away from the Bar. The MACHO survey covering about 10 sq.deg. gives data for 7900 RR Lyraes (Alcock et al. 1996). OGLE III now in progress covers about 40 sq.deg. of the LMC. In the outer field there will often only be one RR Lyrae

²It is worth noting that in this type of work the template used needs to be carefully chosen since strong and weak lines give different velocity amplitudes (e.g. Oke et al. 1962).

in an 8×8 arcmin SALT/PFIS field. It is clear that with the numbers of LMC RR Lyraes known, and surveys still in progress, the only limitations to doing a really good job on the kinematics and metallicities of this old population will be the care taken in the work and the amount of SALT/PFIS time available.

5. RR Lyraes and the SMC

So far as I am aware no spectroscopic studies have yet been published on RR Lyraes in the SMC where these stars are about 0.5mag fainter than in the LMC (i.e $V \sim 19.7$ mag, $B \sim 20.0$ mag). OGLE II gave data on 571 RR Lyraes in a 2.4 sq.deg. field, or about 3 per SALT/PFIS field (Soszyński et al. 2003a). OGLE III covers an SMC area of about 15 sq. deg. It would be particularly interesting to study the kinematics and metallicities of SMC RR Lyraes. Young objects (e.g. Cepheids, Caldwell & Coulson 1986) show the SMC to be very extended in the line of sight, a depth to width ratio of about 5 to 1. The estimated depth is between 15 and 20 kpc. Since at the distance of the SMC, 17kpc corresponds to $\Delta V_o \sim 0.6$ mag, it may be possible to resolve the depth structure in the RR Lyraes.

6. RR Lyraes and the Dwarf Spheroidals

Table 3 lists the dwarf spheroidal galaxies of the Milky Way subgroup in order of their total visual absolute magnitude (taken mostly from van den Bergh 2000). Also listed are estimates of their distance moduli, the numbers of RR Lyraes currently known in each system (with references), the estimated approximate B magnitude of these stars and the numbers expected per SALT/PFIS field. Draco and UMi are of course too far north for SALT (but could usefully be tackled by HET). Detailed studies of clearly old populations in the dwarf spheroidals which are generally supposed to be relatively simple systems would be very valuable. It would of course be in parallel with the high resolution work, some already published (e.g. Shetrone et al. 2003, Tolstoy et al. 2003), on the metallicities of RGB stars in these systems. Whilst the RGB stars are brighter than the RR Lyraes, it seems difficult, at least at present to be certain of the age of single stars of that type. How much will be possible on the dwarf spheroids with SALT will depend on how PFIS actually performs. We might well hope to be able to study the kinematics and metallicities of RR Lyraes in Sextans, Sculptor and Carina, and one might perhaps also hope to observe those in Fornax. It is interesting to note that, so far as I am aware, there has been no published spectroscopic study of the RR Lyraes in the core of the Sgr Dwarf galaxy although these are relatively bright.

7. RR Lyraes in Our Galaxy and the Sgr Dwarf Stream

As regards Our Own Galaxy, some of the outstanding questions are as follows:
 Was the Halo formed from infalling satellites?
 If so, should we see more than the remnants of Sgr Dwarf?
 Can other remnants be found kinematically?

Table 3. The Dwarf Spheroidals of the Milky Way Sub-Group

Galaxy	M_V	Mod	N(RR)	Reference(RR)	$\sim B(RR)$	PFIS
Sgr Dwarf	-13.8:	17.0	2370	1	18.2	1
Fornax	-13.1	20.7	515	2	21.8	15
LeoI	-11.9	22.0	54	3	23.2	3
LeoII	-10.1	21.6	148	4	22.6	40
Sculptor	-9.8	19.7	226	5	21.1	50
Sextans	-9.5	19.7	36	6	20.9	6
Carina	-9.4	20.0	75	7	21.2	4
Draco	-8.4	19.5	263	8		
UMi	-8.4	19.0	56	9		

References

1. Cseresnjes 2001
2. Bessier & Wood 2002
3. Held et al. 2001
4. Siegel & Majewski 2000
5. Kaluzny et al. 1995
6. Mateo, Fischer & Krzeminski 1995
7. Dall'Ora et al. 2003
8. see Dall'Ora et al. 2003
9. Nemec et al. 1988

Is the recently found ring at ~ 20 kpc from the centre (e.g. Ibata et al. 2003, Crane et al. 2003, Sikivie 2003, Helmi et al. 2003, Rocha-Pinto et al. 2003, Martin et al. 2003) a satellite remnant or a structural feature of the galactic disc?

Was the inner halo formed by monolithic collapse or by mixing of infalling debris?

Are the RR Lyraes in the galactic Bulge different from those in the solar neighbourhood or is the Bulge reddening law anomalous? (see, e.g. Stuz, Popowski & Gould 1999, Udalski 2003)

What is the structure of the galactic bar and its relation to the Bulge?

The RR Lyraes in Our Galaxy are relatively thinly distributed over the sky. Even in the main body of Sgr Dwarf there is unlikely to be more than one per SALT/PFIS field. They become somewhat more concentrated in the Bulge where one expects ~ 5 per SALT/PFIS field in the Baade window around NGC6522 (Oort & Plaut 1975). However, there is no lack of galactic RR Lyraes. The SLOAN survey for instance has found 3000 in just 1000 sq.deg. (Ivezic 2003). The SLOAN RR Lyraes extend out to a distance of ~ 100 kpc (i.e. to V magnitudes of 20-21), with clumping probably connected with the Sgr dwarf stream.

The QUEST survey (Vivas et al. 2001, Vivas, Zinn & Gallart 2003, Zinn et al. 2003) is finding large numbers of RR Lyraes (probably with considerable overlap with SLOAN). They report 498 in a 380 sq.deg. region. They also report a clump at a distance of about 50kpc (RR Lyraes with $V \sim 19.2$ mag). For 16 of these they have two spectra each ($R = 800$) from VLT/FORS1. The

radial velocity error for a single measurement is estimated as $\sim 20\text{km s}^{-1}$ and the velocity dispersion of their 16 stars is $\sim 25\text{km s}^{-1}$. This is much lower than that expected for halo objects and is consistent with the suggestion that these stars are part of the Sgr dwarf stream. The mean [Fe/H] of these RR Lyraes is -1.7 .

There is a great deal of work to do here which will clarify our understanding of both the Sgr dwarf (and other) stream(s) and the structure of the halo, including its very outer parts. Currently there is much interest in whether the great-circle structure of the Sgr dwarf stream implies a spherical halo potential, contrary to the predictions of CDM (e.g. Ibata et al. 2001, Majewski et al. 2003, Helmi 2003 and a large number of papers on the Sgr dwarf stream generally). Evidently detailed work on the radial velocities and metallicities of RR Lyraes in the Sgr dwarf stream (and also its core) is of importance both for studies of the structure and evolution of Our Galaxy and also, more generally, for the nature and distribution of dark matter.

8. Conclusion

It is clear that SALT/PFIS will make possible the detailed study of the kinematics and metallicities of RR Lyraes in our own galaxy, in the Magellanic Clouds and in Local Group galaxies. This should lead to a major advance in our understanding of the structure, dynamics, evolution and origin of galaxies. To do this properly will require a major effort but the likely rewards are very considerable. And, if in the process new physics is revealed, so much the better.

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